

# Constraints on planet formation via gravitational instability across cosmic time

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## ABSTRACT

We estimate the maximum temperature at which planets can form via gravitational instability (GI) in the outskirts of early circumstellar disks. We show that due to the temperature floor set by the cosmic microwave background, there is a maximum distance from their host stars beyond which gas giants cannot form via GI, which decreases with their present-day age. Furthermore, we show that planet formation via GI is not possible at metallicities  $\lesssim 10^{-4} Z_{\odot}$ , due to the reduced cooling efficiency of low-metallicity gas. This critical metallicity for planet formation via GI implies a minimum distance from their host stars of  $\sim 6$  AU within which planets cannot form via GI; at higher metallicity, this minimum distance can be significantly larger, out to several tens of AU. We show that these maximum and minimum distances significantly constrain the number of observed planets to date that are likely to have formed via GI at their present locations. That said, the critical metallicity we find for GI is well below that for core accretion to operate; thus, the first planets may have formed via GI, although only within a narrow region of their host circumstellar disks.

**Key words:** Planets and satellites: formation – Cosmology: theory

## 1 INTRODUCTION

When did the first planets form and what were their properties? The answers to these questions depend critically on the process by which the first planets formed. There are two main mechanisms of planet formation that are widely discussed (e.g. Papaloizou & Terquem 2006; Youdin & Kenyon 2012): core accretion, in which dust coagulates into larger and larger bodies which become the cores of planets (e.g. Pollack et al. 1996); and gravitational instability (GI), in which the self-gravity of a circumstellar disk triggers the fragmentation and collapse of gas into a gas giant planet directly (e.g. Boss 1997).

In previous work, we have discussed the formation of the earliest planets via core accretion (see also Shchekinov et al. 2012 for related calculations). In this scenario, we estimated the minimum, or ‘critical’, metallicity to which the gas must be enriched before planet formation can begin (Johnson & Li 2012; hereafter Paper I). We found that the critical metallicity is a function of the distance from the host star, and that the minimum metallicity for the formation of Earth-like planets is likely to be  $\sim 0.1 Z_{\odot}$ . Furthermore, we were able to show that our prediction of the critical metallicity was consistent with the data that were available on planetary

systems, with no planets lying in the ‘Forbidden zone’ in which their metallicities imply formation times longer than the time available (i.e. the disk lifetime).

Recently, however, Setiawan et al. (2012) have announced the discovery of a planet orbiting a star with a very low iron abundance of  $[\text{Fe}/\text{H}] \simeq -2$  (HIP 11952b) which appears to lie in the Forbidden zone for planet formation via core accretion (if this claim proves correct; see Desidera et al. 2013 in prep). This implies that this metal-poor planet likely formed via some other process, such as GI.<sup>†</sup> Furthermore, if it is true that planets can form via GI at metallicities below the critical value for core accretion, then the first planets to form may have been gas giants formed via GI. Terrestrial planet formation (and perhaps the emergence of life), which likely must instead occur via core accretion,<sup>‡</sup> may only occur at later stages of cosmic history when the process of metal enrichment has progressed further. This then raises

<sup>†</sup> Alternatively, this planet may have initially formed closer to its host star via core accretion and then migrated outward.

<sup>‡</sup> Gas giants can be formed via GI, as this process involves the gravitational collapse of gas fragments; terrestrial planets, however, are by definition not gas-dominated and so likely form via some other mechanism, such as core accretion (but see Boley et al. 2010; Nayakshin 2010 on how GI may yield terrestrial planets).

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the question of, instead of the critical metallicity for planet formation via core accretion, what conditions must be satisfied for the first planets to form via GI. Here we address two aspects of this question, namely the impacts of the cosmic microwave background (CMB) and of the reduced cooling efficiency of low-metallicity gas in regulating planet formation via GI.

In the next Section, we review the conditions required for the formation of planets via GI. In Section 3, we consider the constraints placed on this model due to the temperature floor imposed at high redshifts by the CMB, and in Section 4 we estimate the minimum metallicity necessary for planet formation via GI. In Section 5 we compare our predictions for when the first planets form via GI to the available observational data. We give our conclusions in Section 6.

## 2 CONDITIONS FOR PLANET FORMATION VIA GRAVITATIONAL INSTABILITY

We begin by reviewing the conditions required for GI in a circumstellar disk, which we will use to derive constraints on where planets can form in early disks via GI.

The first condition for fragmentation to occur in a thin disk is that  $Q \lesssim 1$ , where (e.g. Toomre 1964; Boss 1998)<sup>§</sup>

$$\begin{aligned} Q &= \frac{0.936 c_s \Omega}{\pi G \Sigma} \\ &\simeq 30 \left( \frac{m_*}{1 M_\odot} \right)^{\frac{1}{2}} \left( \frac{T}{100 \text{ K}} \right)^{\frac{1}{2}} \\ &\times \left( \frac{\Sigma}{10^2 \text{ g cm}^{-2}} \right)^{-1} \left( \frac{r}{10 \text{ AU}} \right)^{-\frac{3}{2}}. \end{aligned} \quad (1)$$

Here  $c_s$  is the sound speed of a gas at temperature  $T$  with mean molecular weight  $\mu = 2$  (close to the value for fully molecular gas) and adiabatic index  $\gamma = 2$ ,  $\Omega$  is the Keplerian angular velocity (which here we assume is identical to the epicyclic frequency),  $\Sigma$  is the surface density of the disk, and  $r$  is the distance from the central host star. In the second equality we have assumed a disk temperature normalized to  $T = 100 \text{ K}$  at  $r = 10$  astronomical units (AU), and a disk surface density normalized to  $\Sigma = 10^2 \text{ g cm}^{-2}$  at  $r = 10 \text{ AU}$ . Finally, we have normalized the above formula to a central stellar mass of  $m_* = 1 M_\odot$ . According to equation (1), fragmentation is only possible in sufficiently dense and/or cold disks, and/or far out from the host star, especially if it is massive. We shall use this condition in Section 3 to derive constraints on planet formation via GI due to the temperature floor set by the CMB.

The second requirement for planet formation via GI is that a circumstellar disk also cools sufficiently fast (see e.g. Gammie 2001; Nayakshin 2006; Levin 2007). Indeed, it is disk cooling which is thought to drive disks to  $Q \simeq 1$  (e.g. Goodman 2003; Thompson et al. 2005). We shall use this condition, along with the requirement that  $Q \simeq 1$ , in Section 4 to explore the limits on first planet formation via GI due to the limited cooling efficiency of low-metallicity gas.

<sup>§</sup> Instabilities leading to fragmentation can occur even for  $Q \simeq 1.4 - 1.7$  (e.g. Mayer et al. 2004; Durisen et al. 2007), but adopting such slightly higher values would not affect our results strongly.

## 3 CONSTRAINTS FROM THE CMB

Here we estimate the maximum temperature at which planet-mass fragments may form and we then use this to derive the limits on planet formation via GI due to the temperature floor set by the CMB.

### 3.1 Minimum Planet Mass

Here we define the minimum mass of a planet formed via GI, as a function of the properties of the disk. We follow Kratter et al. (2010; see also Rafikov 2005; Levin 2007; Cossins et al. 2009; Forgan & Rice 2011) who estimate the initial mass of fragments formed via GI (in a disk with  $Q \simeq 1$ ) as that on the scale of the most unstable wavelength. This yields the following for the minimum planet mass (in units of the mass  $M_J$  of Jupiter):

$$\begin{aligned} m_{\min} &\simeq \Sigma \left( \frac{2\pi c_s}{\Omega} \right)^2 \\ &= 0.5 M_J \left( \frac{m_*}{1 M_\odot} \right)^{-1} \left( \frac{T}{100 \text{ K}} \right) \\ &\times \left( \frac{\Sigma}{10^2 \text{ g cm}^{-2}} \right) \left( \frac{r}{10 \text{ AU}} \right)^3. \end{aligned} \quad (2)$$

Simulations of disk fragmentation via GI also suggest that this is a reasonable estimate for the minimum mass of planets (e.g. Boley 2009; Stamatellos & Whitworth 2009). Indeed, given that this is the initial mass scale of fragments, it is very likely that the final mass they achieve via the continued accretion of gas will be much higher than this value. As noted by Kratter et al. (2010), if such fragments accreted enough gas to attain their isolation mass they will have greatly overshoot the planet mass range and may end up instead as e.g. brown dwarfs. As noted by these authors, it appears that some mechanism must halt accretion in order for planet-mass objects to survive (see also e.g. D'Angelo et al. 2010; Boss 2011). One possibility is that the circumstellar disk is photoevaporated (e.g. Gorti & Hollenbach 2009; Ercolano & Clarke 2010) or otherwise disappears (e.g. Melis et al. 2012) before accretion to super-planet mass scales occurs.

As we shall show next, our adoption of the *minimum* planet mass allows to estimate a *maximum* disk temperature at which planets may form via GI.

### 3.2 Maximum Disk Temperature for Planet Formation

To ensure that fragments which arise in the disk are not too large to be classified as planets we must have  $m_{\min} \lesssim 13 M_J$ , which is the commonly adopted upper mass limit for planets – above this mass deuterium burning occurs and we assume the object to be a brown dwarf. We can combine equation (2) with  $Q = 1$  in equation (1) to obtain the maximum disk temperature  $T_{\max}(r)$  from which a planet of mass  $m_{\min}$  can form from fragmentation of the disk:

$$T_{\max} \simeq 100 \text{ K} \left( \frac{m_*}{1 M_\odot} \right)^{\frac{1}{3}} \left( \frac{m_{\min}}{13 M_J} \right)^{\frac{2}{3}} \left( \frac{r}{10 \text{ AU}} \right)^{-1}, \quad (3)$$

where we have normalized to the maximum planet mass of  $m_{\min} = 13 M_J$ . If the temperature of the disk exceeds

this value, then planet formation via GI may be impossible, either because fragmentation is suppressed (see equation 1), or if fragmentation occurs the fragment(s) form with super-planetary masses (becoming e.g. brown dwarfs instead of planets; see equation 2). While temperatures below this maximum value may be necessary for planet formation (and are found in simulations including radiative cooling; e.g. Nelson et al. 2000; Mejía et al. 2005; Boley et al. 2006; Forgan et al. 2011), they are not alone sufficient. In addition, the surface density of the disk must also be high enough that  $Q \lesssim 1$  (equation 1), and in the case of non-isothermal disks the cooling criterion of Gammie (2001) must also be satisfied. ¶

### 3.3 The CMB temperature floor

It is well-known that gas cannot cool radiatively to temperatures lower than that of the CMB, given by  $T_{\text{CMB}} = 2.73 \text{ K} (1+z)$ , where  $z$  is redshift. Therefore, planet formation will not be possible if it requires that the disk cools below  $T_{\text{CMB}}$ . ¶ Following equation (3), this implies that at high redshifts planet formation can only occur relatively close to the host star. We can express this maximum radius  $r_{\text{max}}$  for planet formation, as a function of the host star mass  $m_*$  and redshift  $z$ , by equating  $T_{\text{CMB}}$  to the maximum disk temperature for planet formation given by equation (3). This yields

$$r_{\text{max}} \simeq 40 \text{ AU} \left( \frac{m_*}{1 M_\odot} \right)^{\frac{1}{3}} \left( \frac{m_{\text{min}}}{13 M_J} \right)^{\frac{2}{3}} \left( \frac{1+z}{10} \right)^{-1}. \quad (4)$$

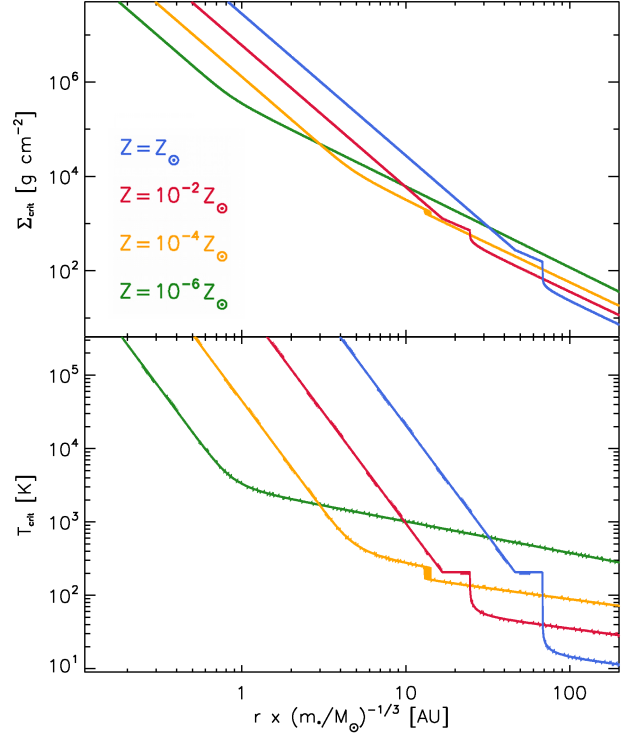
Therefore, even for the highest mass stars that may have survived to the present day ( $\simeq 0.8 M_\odot$ ), planets can only form inside  $r \lesssim 40 \text{ AU}$  at  $z \gtrsim 10$ , roughly the epoch of the first metal-enriched star formation in the earliest galaxies (e.g. Bromm & Yoshida 2011). Thus, we would expect such old planets formed via GI to be found on relatively tight orbits around old, low-mass, metal-poor stars. In the next Section, we estimate how tight these orbits can be, given the limited cooling properties of metal-poor gas.

## 4 CONSTRAINTS AT LOW METALLICITY

To explore the effect of metallicity on the fragmentation properties of circumstellar disks, we impose the two conditions required for planet formation via GI described in Section 2. We follow the common approach of estimating the cooling rate of the disk based on its opacity (e.g. Rafikov 2005; Levin 2007; Kratter et al. 2010), which we assume to be proportional to the metallicity of the disk. Specifically, we follow exactly the calculation presented by Levin (2007), for four different metallicities:  $Z = 10^{-6}, 10^{-4}, 10^{-2}$ , and  $1 Z_\odot$ . We use the opacities for solar metallicity gas  $\kappa(Z_\odot)$  given

¶ We note that the cooling criterion has been shown to always be met for isothermal disks and disks subjected to external irradiation (Kratter & Murray-Clay 2011).

¶ The suppression of planet formation via GI due to background radiation fields has been confirmed by e.g. Stamatellos & Whitworth (2008), Cai et al. (2008) and Forgan & Rice (2013), although these authors did not consider the effect of the CMB in particular (see also Cossins et al. 2010; Rice et al. 2011; Zhu et al. 2012).

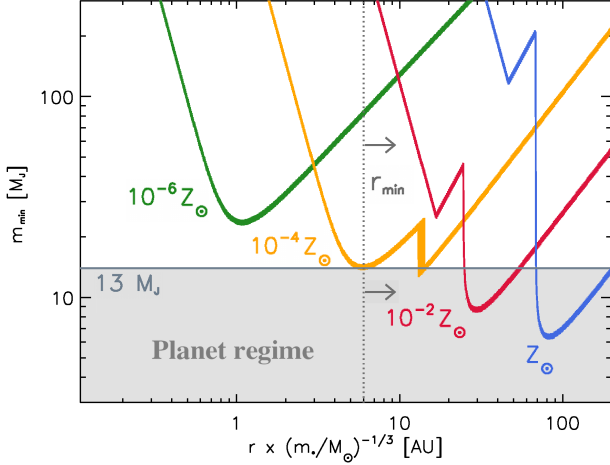


**Figure 1.** The critical surface density  $\Sigma_{\text{crit}}$  (top panel) and temperature  $T_{\text{crit}}$  (bottom panel) at which circumstellar disks fragment, as functions of distance from the host star in circumstellar disks of various metallicities, as labeled. The kinks in the curves are due to breaks in the functional fit to the opacity, as a function of temperature, we have adopted from Bell & Lin (1994).

by equation (9) of Levin (2007; from Bell & Lin 1994), and we scale them with metallicity, such that  $\kappa(Z) = \kappa(Z_\odot) \times (Z/Z_\odot)$ . From this, we solve for the critical surface density  $\Sigma_{\text{crit}}$  and temperature  $T_{\text{crit}}$  at which the effective viscosity of the disk reaches the critical value of  $\alpha_{\text{crit}} = 0.3$  (Gammie 2001) and the disk fragments. These are shown in Figure 1, for the various metallicities we consider. We then use these critical values for the surface density and temperature in equation (2) to find the minimum mass  $m_{\text{min}}$  of fragments formed. The values we find for  $m_{\text{min}}$ , as functions of the mass  $m_*$  of and distance  $r$  from the host star, are shown in Figure 2.

For the case of solar metallicity, we successfully reproduce the results presented by Levin (2007), as expected. \*\* For the lower metallicity cases, the effect of the reduced opacity of the disk is that the critical temperature  $T_{\text{crit}}$  and surface density  $\Sigma_{\text{crit}}$  are significantly higher (lower) at large (small) radii, as shown in Fig. 1. In turn, this translates into larger minimum fragment masses at smaller radii, at lower metallicities, as shown in Fig. 2. At solar metallicity, our result for the minimum fragment mass is similar to that found by e.g. Rafikov (2005), and our result that fragmen-

\*\* But note that we have adopted a more widely used formula for  $m_{\text{min}}$  (equation 2; e.g. Rafikov 2005; Cossins et al. 2009; Kratter 2010). Also, we have used Kepler's Law to convert from the rotation period of the disk, in which the results are presented by Levin (2007), to the distance  $r$  out from the central star.



**Figure 2.** The minimum fragment mass  $m_{\min}$  as a function of distance from the host star in circumstellar disks of various metallicities, as labeled. The critical metallicity for planet formation via GI is  $Z_{\text{crit}} \simeq 10^{-4} Z_{\odot}$ , as below this metallicity the  $m_{\min} \geq 13 M_{\text{J}}$ , the maximum planet mass. This corresponds to a minimum distance from the host star of  $r_{\min} \simeq 6$  pc (for  $m_{*} \simeq 1 M_{\odot}$ ), shown by the dotted line. At  $r \leq r_{\min}$  planet formation via GI is not possible. As the curves at  $10^{-2}$  and  $1 Z_{\odot}$  show,  $r_{\min}$  is even larger at higher metallicity; hence the arrows denoting the value of  $r_{\min}$  shown here to be a lower limit. Note that  $m_{\min}$  increases at large radii, despite the decrease in  $\Sigma_{\text{crit}}$ , due to its strong  $r$ -dependence via  $\Omega(r)$  in equation (2).

tation into planet-mass objects is still possible even at  $10^{-2} Z_{\odot}$  is similar to that found by Meru & Bate (2010), assuming a metallicity dependent opacity similar to what we have adopted (see also e.g. Boss 2002; Cai et al. 2006; Helled & Bodenheimer 2011 on the susceptibility of low-metallicity disks to GI). Our calculation is also broadly consistent with previous work which has shown that planet formation via GI is difficult to achieve within tens of AU at metallicities near the solar value (Stamatellos & Whitworth 2008; Clarke & Lodato 2009; Rice & Armitage 2009; Rogers & Wadsley 2011; Kimura & Tsuribe 2012; Vazan & Helled 2012), as discussed by e.g. Boley et al. (2009) and Boss (2012).

At metallicities  $Z \lesssim 10^{-4} Z_{\odot}$  there exists no region of the disk where  $m_{\min} \lesssim 13 M_{\text{J}}$ , the maximum planet mass; therefore, we interpret this to be the critical metallicity for planet formation via GI. This critical metallicity for GI is well below that for core accretion (Paper I), which implies that the first planets may well have formed via GI in very low-metallicity circumstellar disks in the early universe. We note furthermore that this critical metallicity is below estimates of the metallicity to which the primordial gas is enriched by the first supernovae ( $\simeq 10^{-3} Z_{\odot}$ ; e.g. Wise & Abel 2008; Greif et al. 2010), and this suggests that the first planets may have even formed around second generation stars via GI.

As shown in Fig. 2, at successively lower metallicity, the minimum fragment mass drops into the planetary regime at smaller radii. Thus, the critical metallicity also implies a minimum distance  $r_{\min}$  from their host stars at which planets can form via GI. From Fig. 2, we see that at the critical metallicity of  $\simeq 10^{-4} Z_{\odot}$ , this minimum distance is  $r_{\min} \simeq 6$  AU, for a  $m_{*} \simeq 1 M_{\odot}$  host star. The exact value of  $r_{\min}$

changes slightly for different host stellar masses, with  $r_{\min} \propto m_{*}^{1/3}$  as shown on the x-axis in Fig. 2. At separations smaller than the  $r_{\min}$  shown in Fig. 2, the minimum fragment mass is super-planetary, regardless of the metallicity of the gas. We plot this value for  $r_{\min}$  in Figure 3 to show how this minimum distance and the  $r_{\max}$  we found in Section 3 bracket a region in which planet formation via GI is possible. We refer to the region inside  $r_{\min}$  as the ‘metal cooling-prohibited’ region, as it is ultimately the limited cooling efficiency of the gas at low metallicities that sets the critical metallicity corresponding to  $r_{\min}$ . From Fig. 3, we see that just  $\sim 100$  Myr after the Big Bang the CMB temperature drops to values low enough to make  $r_{\min} \leq r_{\max}$ , and so for planet formation via GI to proceed. Thereafter, planets can form via GI in larger regions of their host circumstellar disks at later cosmic times.

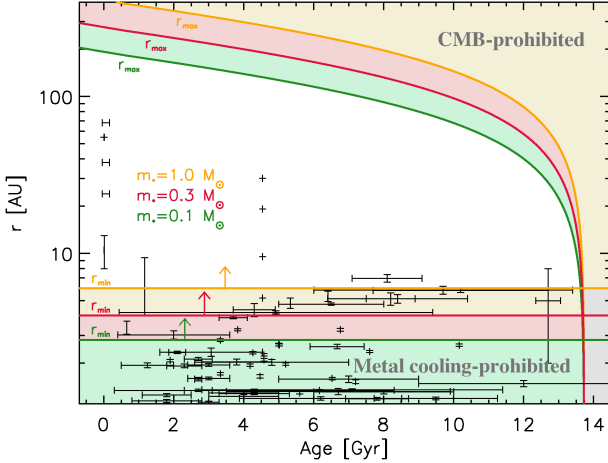
Another key point that is evident from Fig. 2 is that at higher metallicity  $r_{\min}$  becomes larger, further constraining the radii in metal-enriched circumstellar disks in which planet formation via GI is possible. In particular, at  $Z \gtrsim 0.1 Z_{\odot}$  we find that  $r_{\min} \gtrsim 50$  AU, which is larger than  $r_{\max}$  set by the CMB at  $\lesssim 2$  Gyr after the Big Bang (or at  $z \gtrsim 3$ ), as shown in Fig. 3. This suggests that planet formation via GI may be difficult to achieve at metallicities higher than just  $\sim 10$  percent of the solar value at these early times.

While in Fig. 3 we present our results for the CMB-prohibited regime and the metal cooling-prohibited regime independently, in principle they are most realistically considered together, since at high redshift the metallicity of circumstellar disks is likely lower and the CMB temperature is higher *at the same time*. It is for simplicity that we have treated these effects separately, in part because the spatially inhomogeneous nature of metal enrichment implies that there is no clear one-to-one mapping between redshift (or  $T_{\text{CMB}}$ ) and metallicity. That said, we emphasize that self-consistently including the effect of background irradiation in our calculations could result in somewhat larger fragments (see e.g. Levin 2007; Forgan & Rice 2013), which in turn would raise the critical metallicity that we find in Fig. 2. As shown in Fig. 3, at early times the temperature of the CMB may indeed be high enough to effect such a change.

## 5 COMPARISON WITH DATA

Here we compare our theoretical predictions of  $r_{\max}$  set by the CMB and  $r_{\min}$  set by the critical metallicity for GI with the star-planet separations inferred from observations. This allows to test whether GI is a viable explanation for the formation of the oldest known planets. In Fig. 3, we make this comparison, plotting the semimajor axes and host stellar ages of planets compiled in Wright et al. (2011)<sup>††</sup> with host stars having sub-solar iron abundance ( $[\text{Fe}/\text{H}] < 0$ ), which we take as an indicator of old age. We have also included the four gas giants in our Solar System, as well as the metal-poor planetary systems reported by Sigurdsson et al. (2003) and Setiawan et al. (2012), and the wide orbit planets reported by Chauvin et al. (2004), Marois et al. (2008) and Lagrange et al. (2010). Here we have taken the Sigurdsson et

<sup>††</sup> We have taken the data directly from exoplanets.org.



**Figure 3.** The semimajor axes (*vertical axis*) and host stellar age (*horizontal axis*) of planets, as described in Section 5, along with any reported error in these quantities. The top series of colored lines show the maximum possible distances  $r_{\max}$  at which planets can form from their host stars via GI, as a function of their present age (see equation 4), for four different host stellar masses as labeled. Beyond this maximum distance it is predicted that planet formation is not possible via GI, due to the CMB temperature floor. We term this region the ‘CMB-prohibited’ zone. The bottom series of colored lines show the minimum possible distances  $r_{\min}$  at which planets can form via GI (see Section 4), which is set by the limited cooling efficiency of metal-poor gas and hence defines here the ‘metal cooling-prohibited’ zone. As shown in Fig. 2, the values of  $r_{\min}$  given here are lower limits corresponding to metallicities just at the critical value of  $Z_{\text{crit}} \simeq 10^{-4} Z_{\odot}$ ; at higher metallicity  $r_{\min}$  is larger. Only a handful of known planets fall between these two zones, and so could have formed via GI at their present locations.

al. (2003) host stellar age to be that of the globular cluster in which it was found, and the semimajor axis is taken to be its original one inferred from the modeling done by these authors.

Also shown in Fig. 3 are the maximum radii of formation  $r_{\max}$  for planets orbiting stars of three different masses: 0.1, 0.3 and  $1 M_{\odot}$ , following equation (4) with the maximum planet mass of  $m_{\min} = 13 M_{\text{J}}$ .<sup>‡‡</sup> To facilitate the comparison with the ages of the observed planetary systems, we have converted from redshift  $z$  (in which  $r_{\max}$  is expressed in this equation) to the time elapsed since redshift  $z$ , following the formulae describing Hubble expansion in the standard  $\Lambda$ CMD cosmology presented in e.g. Barkana & Loeb (2001) and assuming a flat universe with the following cosmological parameters:  $H_0 = 70.3 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_{\Lambda} = 0.73$  and  $\Omega_{\text{M}} = 0.27$  (Komatsu et al. 2011). We expect the CMB temperature floor to suppress the formation of planet-mass objects at radii  $\gtrsim r_{\max}$ , in the upper shaded region of Fig. 3. We term this the ‘CMB-prohibited’ zone.

<sup>‡‡</sup> We have chosen to plot the curves for this single maximal planet mass  $m_{\min}$ , since most of the data imply only a lower limit to their mass, meaning that such a high mass can not in general be ruled out. We emphasize, however, that the region in which planet formation is suppressed is larger for planets with lower masses (see equation 4 and Fig. 2).

All of the planets shown in Fig. 3 appear to lie at radii much smaller than  $r_{\max}$ , in part because most are relatively young (e.g.  $\lesssim 10$  Gyr old) and formed at times when the temperature of the CMB was low. We also note that Boss (2011) argues that the formation of wide orbit gas giants, such as those shown at  $\gtrsim 20$  AU, may be best explained by GI, especially if they are formed around relatively massive stars, consistent with the curves in Fig. 3.

There are additional candidate planets with very wide orbits that are not included in Fig. 1. These candidates, reported by Kalas et al. (2008) and Lafrenière et al. (2008; 2010), respectively, would lie at  $\simeq 115$  AU and  $\simeq 150$  AU from their host stars, which have masses of  $\simeq 1.9 M_{\odot}$  and  $\simeq 1 M_{\odot}$ , and ages of just  $\simeq 0.4$  Gyr and  $\simeq 5$  Myr (see also Béjar et al. 2008; Bowler et al. 2011; and Ireland et al. 2011 for other very wide orbit  $\simeq 14 M_{\text{J}}$  companions). If veritable planets, they would lie just outside the CMB-prohibited zone and so may have formed via GI at their present locations. Alternatively, they could have formed at smaller radii and migrated outward (e.g. Veras et al. 2009; but see Dodson-Robinson et al. 2009; Bowler et al. 2011) or originated as free-floating planets (Perets & Kouwenhoven 2012; Strigari et al. 2012).<sup>§§</sup>

While the planets shown in Fig. 3 lie well below the CMB-prohibited zone, there are only a few planets that are outside the metal cooling-prohibited zone, at  $r \gtrsim 6$  AU. Thus, unless they migrated inward from larger radii, it appears that there are only a handful of known planets that could have formed via GI. In particular, this is the case for the planets reported by Setiawan et al. (2012). While they orbit a star with  $[\text{Fe}/\text{H}] \simeq -2$ , suggesting that they formed from gas with metallicity well above the critical metallicity for GI, they lie at  $r \lesssim 0.81$  AU, well within  $r_{\min} \simeq 6$  AU. Importantly, however, given the old age of  $\simeq 12.8$  Gyr inferred for this planetary system, if there is indeed a larger  $r_{\min}$  of  $\sim 25$  AU for circumstellar disks at this metallicity (and for the mass  $m_{*} \simeq 0.8 M_{\odot}$  inferred for its host star), as suggested by Fig. 2, then this would pose a strong challenge to GI as an explanation even in this case.

Finally, we note that it has been suggested that planets currently on relatively tight orbits around their host stars may have formed from the collapse of significantly more massive (perhaps super-planetary) fragments at larger radii, which then migrated inward and lost mass due to tidal shear or stellar irradiation (Nayakshin 2010). If this process is indeed at play, then it is possible that some of the planets in Fig. 3 may have originated from GI, despite residing in the metal cooling-prohibited zone today.

<sup>§§</sup> Migration and/or capture by the host star are important caveats to consider with regard to conclusions drawn from comparison with data, which only reflect where the planets orbit their host stars today. In particular, we note that inward migration is especially likely for planets formed via GI (e.g. Baruteau et al. 2011), which could potentially place some of the planets in Fig. 1 in the CMB-prohibited zone at their formation, or place some of those currently within  $r_{\min}$  in between  $r_{\min}$  and  $r_{\max}$  at their formation.

## 6 CONCLUSIONS

As an alternative to the core accretion model for the formation of the first planets (discussed in Paper I), we have considered here the formation of the earliest planets via GI.

We have argued that there is a maximum circumstellar disk temperature only below which can planets form via GI. In turn, this implies a maximum distance from their host stars at which planets can form via GI due to the temperature floor set by the CMB. As the CMB temperature is higher at earlier times, planets may only form via GI at distances from their host stars which decrease with their present-day age.

We have furthermore estimated the minimum metallicity required for the fragmentation of circumstellar disks into planet mass objects. We find that this critical metallicity for GI is  $Z_{\text{crit}} \simeq 10^{-4} Z_{\odot}$ , well below that for core accretion. In turn, because planet formation via GI is possible at smaller distances from the host star at lower metallicities, this critical metallicity implies a minimum distance of a few AU at which planets can form via GI.

These two limits together imply that, while planet formation via GI can take place at metallicities below those required for core accretion, it can only occur at metallicities  $\gtrsim 0.1 Z_{\odot}$  at times  $\gtrsim 2$  Gyr after the Big Bang. In particular, this does not rule out that the first planets in the Universe may indeed have formed via GI at metallicities  $10^{-4} \lesssim Z \lesssim 10^{-1} Z_{\odot}$  during the epoch of the first galaxies,  $\sim 500$  Myr after the Big Bang (e.g. Bromm & Yoshida 2011).

That said, we find that there are only a handful of known planets which lie within the bounds of the metal cooling- and CMB-prohibited zones in which planets can form via GI. It may be, however, that some known planets could have migrated inward from their formation sites outside the metal cooling-prohibited zone. This may explain, in particular, the existence of the very low-metallicity planets reported by Setiawan et al. (2012), the formation of which is otherwise difficult to explain in the core accretion model.

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